Application of Hybrid Lidar-Radar Technology to a Laser Line Scan System

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LONG-TERM GOALS

The long-term goal of this program is to use hybrid lidar-radar technology to improve underwater laser imaging performance in turbid water and in high solar background environments.

OBJECTIVES

The objective of this program is to investigate the application of hybrid lidar-radar technology to a laser line scan system to enhance detection sensitivity in turbid water and high solar background environments. The results will be transitioned to underwater laser imaging systems, such as the Coastal Systems Station (CSS, Panama City)/Raytheon Laser Line Scanner (LLS).

APPROACH

This project will focus on the application of the hybrid lidar-radar approach to a LLS sensor. Both laboratory tank experiments and in-situ pier experiments will be conducted to test a modulated LLS sensor which has similar characteristics to an existing LLS system, the Coastal Systems Station (CSS, Panama City)/Raytheon LLS. The new system will be compared to its unmodulated counterpart in terms of backscatter and blur/glow/forward scatter signal levels and solar ambient noise. Concurrent with these experiments, higher modulation frequencies and coherent detection schemes will be investigated to determine whether more advanced system configurations would further improve LLS sensor performance. Inputs from Drexel University (Dr. Peter Herczfeld) on the current state-of-the-art in modulated transmitter and receiver components will be requested for this task. An analytical model has been developed by Dr. Eleonora Zege at the National Academy of Sciences of Belarus to predict the performance of current and future modulated laser imaging systems.

WORK COMPLETED

In the first year of the program, a modulated laser line scanner prototype was designed and developed with off-the-shelf components. Experiments were conducted in a laboratory water tank and the results showed an improvement in target contrast with increasing modulation frequency. In the second year of the program, in-situ experiments were conducted from a pier in the Patuxent River to test the modulated LLS prototype in turbid water and in a high solar background environment. The main purpose of these tests was to determine the effect of modulation frequency and target depth on the amplitude and phase of the modulated optical signal. These in-situ tests produced results similar to those obtained in laboratory measurements: the contrast improved with increasing modulation

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14. ABSTRACT
The long-term goal of this program is to use hybrid lidar-radar technology to improve underwater laser imaging performance in turbid water and in high solar background environments.

15. SUBJECT TERMS

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frequency due to a corresponding decrease in backscatter. Additional tests produced fluctuations in the target return data that were linked to constructive and destructive interference effects. The primary accomplishment of FY01 was developing a theoretical model to predict modulated LLS performance and comparing the model results with both laboratory and in-situ experimental data collected during the previous years of the program.

RESULTS

Techniques for solving the nonstationary radiative transfer equation specifically for the case of modulated light beam propagation have been developed and are based on pulse propagation theory. Although numerical methods (such as Monte Carlo simulations) allow one to compute pulse propagation and reflection from localized sources, only analytical approaches were studied due to the excessive computation time required for numerical techniques in highly scattering media. The analytical solution is based on a combination of several techniques, including the Small Angle Diffusion Approximation (SADA) and the Multi-Component Method (MCA) for simplifying the stationary problem, and the method of moments to solve for the nonstationary light field distribution. Although only the model results are discussed below, a more detailed explanation of the analytical approach can be found in [1].

Since the ultimate goal was to compare the model and experimental results, the theory was developed to closely model the experimental setup. The power of the signal arriving at the receiver consisted of two components: the power of the backscatter noise (BSN), P_{BSN}, and the power of the signal reflected from the target, P_{ob}. The theory was used to calculate these two quantities as a function of modulation frequency for the relevant experimental parameters. Experimental parameters incorporated into the model include the transmitted beam size and divergence, the water optical properties, the target size, reflectivity and depth, and the receiver aperture and field of view.

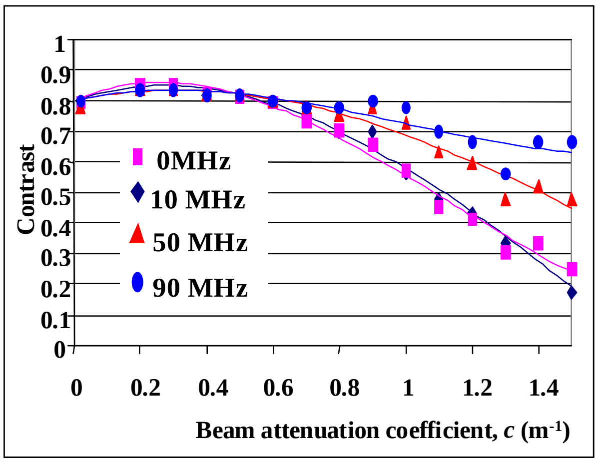
The first set of experimental data was obtained in a laboratory tank environment in the first year of the program [2]. Parameters of the experimental setup, including the geometry and the optical parameters of the tank water, are shown in Table 1. Varying solutions of Maalox antacid in tap water were used to simulate different water types. Both black and white targets were used in the experiment, and the target contrast was defined as

$$k = \frac{|P_{\mathrm{ob}}(A_{white},\omega) + P_{\mathrm{BSN}}(\omega)| - |P_{\mathrm{ob}}(A_{black},\omega) + P_{\mathrm{BSN}}(\omega)|}{|P_{\mathrm{ob}}(A_{white},\omega) + P_{\mathrm{BSN}}(\omega)| + |P_{\mathrm{ob}}(A_{black},\omega) + P_{\mathrm{BSN}}(\omega)|}$$

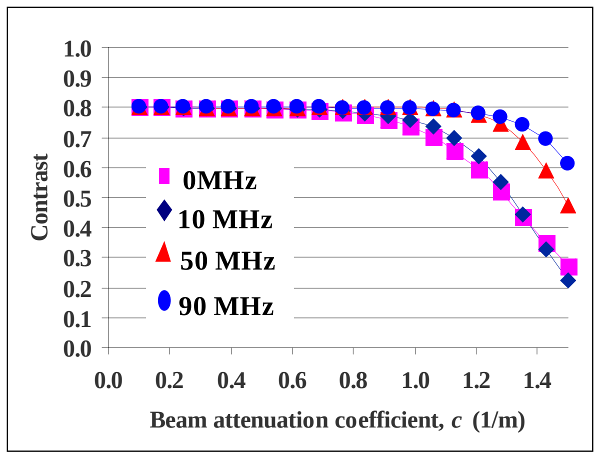
where $P_{\mathrm{ob}}(A_{white}, \omega)$ and $P_{\mathrm{ob}}(A_{black}, \omega)$ are the signal returns from the white and black targets, respectively, at a particular modulation frequency, ω. The experimental and theoretical results are shown in Figures 1a and 1b, respectively, where the target contrast is plotted as a function of the beam attenuation coefficient, c, for no modulation (0 MHz) and for three different modulation frequencies (10, 50, and 90 MHz). In both cases, the contrast decreased for increasing beam attenuation coefficient for all modulation frequencies. Similarly, for both the 0 and 10 MHz data, the theoretical and experimental contrasts overlapped for all water clarities. Both data sets also showed an improvement in target contrast for increasing modulation frequency for water clarities above c=0.8m^{-1}.

Table 1. Parameters of the experimental setup used to obtain the data in Figures 1a and 1b.

<SOURCE>		<GEOMETRY>	
Aperture, m	0.005	Object depth, m	3.7
FOV, rad	0.005	Source-Receiver base, m	0.43
<RECEIVER>		Source/Receiver axis intersect at the object center	
Aperture, m	0.05	<WATER>	
FOV, rad (full angle)	0.026	Absorption coefficient, 1/m	0.06
<OBJECT>		Scattering properties are simulated by the addition of Maalox antacid.	
Diameter, m	0.9		
Albedo white object	0.9		
Albedo black object	0.1		



a.[Experiment]



b.[Theory]

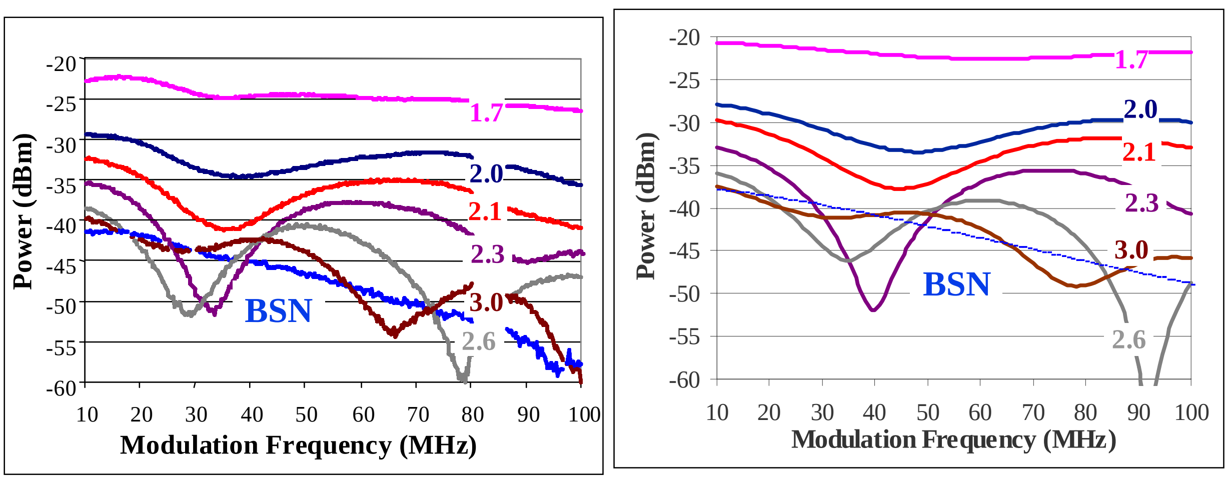
Figure 1. Experimental (a) and theoretical (b) results obtained with the parameters listed in Table 1. The target contrast is plotted as a function of beam attenuation for four modulation frequencies, 0, 10, 50, and 90 MHz.

The next set of experimental data was obtained in an in-situ environment in the second year of the program [3]. The various experimental parameters that were used in the simulation are shown in Table 2. The signal reflected from a square white target was measured as a function of modulation frequency (10-100MHz) and at various depths from 1.7-3 m. The backscatter signal (BSN) was also measured as a function of modulation frequency. The experimental and corresponding theoretical results are shown in Figures 2a and 2b, respectively. It is important to note that some of the optical properties of water, particularly the scattering phase function, were not measured at the test site and therefore could not be used as inputs to the simulation. Therefore, the water optical properties were estimated directly from the measured data. For example, the missing parameters were adjusted so that the backscatter noise power (labeled 'BSN' in Figure 2b) was at a level of –40dBm at a modulation frequency of 10MHz.

In spite of the uncertainty of the optical parameters, the results in Figures 2a and 2b show reasonable agreement. For example, the backscatter signal in both experiment and theory decays approximately 20dB as the modulation frequency increased. Furthermore, the theory was able to reproduce the fluctuations in the target return data that became evident as the target amplitude approached the backscatter signal level. The locations of the minima and maxima of these fluctuations also changed with target depth in both cases. An explanation for these results is that the reflection of the modulated optical signal from the target interacted with the backscatter signal to produce constructive and destructive interference at the receiver.

Table 2. Parameters of the experimental setup used for the data in Figures 2a and 2b.

<SOURCE>		<GEOMETRY>	
Aperture, m	0.005	Source-Receiver base, m	0.2
FOV, rad	0.005	Source and Receiver axis are parallel	
<RECEIVER>		<WATER>	
Aperture, m	0.05	Extinction coefficient, 1/m	3.88
FOV, rad (full angle)	0.07	Absorption coefficient, 1/m	0.4
<OBJECT>			
Diameter, m	1.2		
Albedo white object	0.9		



a. [Experiment] *b. [Theory]*

Figure 2. Experimental (a) and theoretical (b) results obtained with the parameters listed in Table 2. The power of the target and backscatter (BSN) return signals are plotted as a function of modulation frequency for several depths

In summary, the primary results obtained in the third year of this program are that we successfully

1. developed an analytical model to characterize modulated light beam propagation in scattering media;
2. incorporated experimental parameters into the model that closely resemble laboratory and in-situ tests conducted in previous years of the program; and
3. compared theoretical and experimental results to test the accuracy of the model.

The significance of these accomplishments is that we now have a powerful tool to study the effect of many variables on hybrid lidar-radar performance, including water clarity, system configuration, and target characteristics. By comparing experimental and theoretical results, we have a better understanding of the sensitivity of the model to its inputs. For example, we acknowledge the importance of accurately measuring the water optical properties (such as the scattering phase function) to obtain good correlation between experiment and theory. In spite of the uncertainty of the seawater optical parameters in the experimental studies, a reasonable agreement between theoretical and experimental data was found.

IMPACT/APPLICATIONS

The hybrid lidar-radar technology has the potential to improve underwater laser imaging systems (such as the laser line scanner) by

1. reducing backscatter and solar ambient noise
2. enhancing target contrast.

The theoretical model developed in the third year of this project is a powerful tool to better understand the benefits and limitations of the hybrid lidar-radar approach. This model will also help us to investigate more sophisticated system configurations, such as higher modulation frequencies and different radar modulation techniques, which are difficult to test experimentally. The model is also flexible enough to incorporate optical properties of other optically dense media, including clouds, fog, smoke and biological tissue. Therefore, we can study the application of the hybrid lidar-radar technology to other laser imaging systems that are also limited by optical scattering.

TRANSITIONS

The technology developed in this program can be transitioned to the CSS/Raytheon LLS, as well as to other contrast-limited underwater laser imaging systems (i.e., EOID, Claymore Marine, ALMDS, Lotus). DARPA (Ray Balcerak) has provided seed funding to investigate the application of hybrid lidar-radar technology to improve imaging through clouds, fog, and smoke. A patent application has also been submitted for the medical diagnostics application of hybrid lidar-radar technology.

RELATED PROJECTS

Collaboration between NAWCAD, Patuxent River, MD (L. Mullen and V. Contarino), NSWC, Panama City, FL (M. Strand), and Raytheon Company, Tewksbury, MA (B. Coles) was needed to develop the modulated laser line scanner prototype. Results from the tank and pier experiments continue to be shared with this research group to help identify transition potentials for the modulated laser imaging system. The other closely related project is that which includes Drexel University (http://www.drexel.edu). Dr. Peter Herczfeld at Drexel is supervising work in advanced component development for future modulated laser imaging systems, including high speed detectors and high frequency optical modulators. Close collaboration with Dr. Eleonora Zege and her group at the National Academy of Sciences of Belarus was also needed to develop, test, and evaluate the theoretical model for modulated light beam propagation.

REFERENCES

[1] L. Mullen, E. Zege, “Modulated Lidar System: Experiment and Theory,” to be published in the *Proceedings of SPIE, the International Symposium on Optical Science and Technology*, San Diego, CA, July29 – August 3, 2001.

[2] L. Mullen, V. M. Contarino, A. Laux, B. Concannon, J. Davis, M. Strand, B. Coles, “Modulated Laser Line Scanner for Enhanced Underwater Imaging,” *Proceedings of the SPIE Annual Meeting*, July 18-23, 1999.

[3] L. Mullen, V. M. Contarino, B. Concannon, A. Laux, “Modulated Laser Measurements in the Patuxent River,” *Proceedings of Ocean Optics XV*, Monte-Carlo, Monaco, October 16-20, 2000.

PUBLICATIONS

L. Mullen, P. R. Herczfeld, V. M. Contarino, “Progress in Hybrid Lidar-Radar for Ocean Exploration,” *Sea Technology*, Vol. 37, no. 3, pp. 45-52, March, 1996.

L. Mullen, P. R. Herczfeld, V. M. Contarino, “Novel Hybrid System Spots Submarines,” *Photonics Spectra*, p. 20, July, 1996.

L. Mullen, V. M. Contarino, P. R. Herczfeld, “Hybrid Lidar-Radar Ocean Experiment,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 44, no. 12, December, 1996, pp. 2703-2710.

L. Mullen, V. M. Contarino, P. R. Herczfeld, “Intracavity Phase Modulated Transmitter for Hybrid Lidar-Radar,” *Optics & Photonics News*, Vol. 7, no. 12, December, 1996, pp. 42-43.

L. Mullen, “Modulated Lidar System for Underwater Detection and Imaging,” Invited paper submitted to the April, 2000 special issue of U. S. Navy Journal of Underwater Acoustics (JUA(USN)) for ASW investigations.

L. Mullen, and V. M. Contarino, “Hybrid Lidar-Radar: Seeing through the Scatter,” *IEEE Microwave Magazine*, Vol. 1, (2000), pp. 42-48.

PATENTS

L. Mullen, V. Contarino, P. Herczfeld, *Hybrid Lidar-Radar for Medical Diagnostics*, Submitted February 5, 2001 (Navy Case No. 82987)